Very Large Antenna Array Activity at JPL and Caltech for Space Communications and Radio Astronomy

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Outline

1. Rationale for array for deep space communications (DSN)

2. Baseline 5m antenna element
   A. Specifications
   B. Stamped aluminum paraboloid
   C. An approach to the mount design

3. Cost estimate for SKA antenna and receivers

4. Wideband integrated circuit low-noise receivers

5. Summary of technology approach

6. Signal processing

7. A proposed schedule

Acknowledgement

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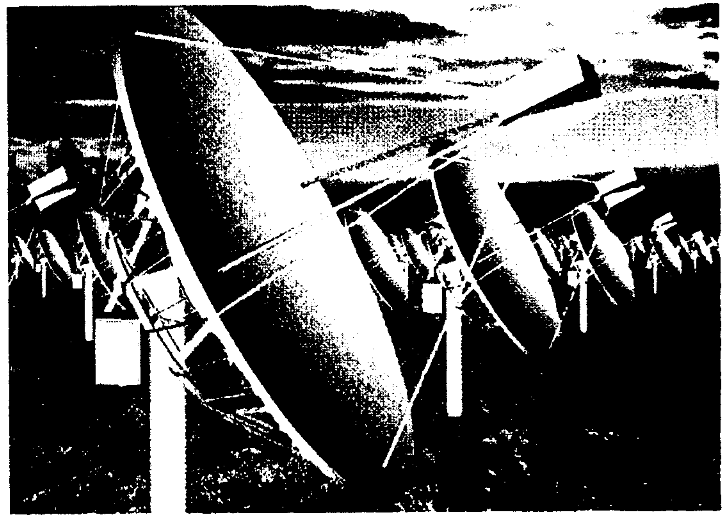
JPL

A DSN Array for the 21'st Century

- **Need** - More missions, at greater distance, with smaller spacecraft, and higher data-rate science instruments

- **Commercial Technology Developments Have Drastically Reduced Array Costs** - Satellite TV industry is producing small antennas and very low noise receivers at amazing costs.

- **Very Large Improvement is Feasible** – A 4000 element array of 5-meter antennas can provide a factor of 10 improvement of both 8 and 32 GHz receiving capability compared to a 70m antenna at a cost of under $300M.



Powerful Advantages of a Dispersed Array

- With 1000 km spacing tracking accuracy is 1km at the distance of Mars.
- Multiple beams can simultaneously communicate with several spacecraft
- Array partitioning allows "just enough" communication for multiple missions.
- Soft failure; weather diversity; low cost risk

Comparison of Existing Large Antennas and Future Arrays

February 28, 2000

Antenna	Elements	Effective Area	Upper Frequency	Tsys	A/Tsys
DSN 70m	1 x 70 m	2,607	8 to 32 GHz	18	145
GBT	1 x 100 m	5,700	100 GHz	20	285
VLA	27 x 25 m	8,978	43 GHz	32	280
Arecibo	1 x 305 m	23,750	8 GHz	25	950
ALMA	64 x 12 m	4,900	1000 GHz	50	98
1HT	509 x 5 m	6,770	11 GHz	35	193
SKA -1KT	TBD	1,000,000	20 GHz	50	20,000
DSN Array	**4000 x 5 m**	**53,200**	**8 & 32 GHz**	**30**	**1,773**

DSN Array Communication Improvement Relative to DSN 70m Antennas

Antenna	dB Improvement at 8.4 GHz	dB Improvement at 32 GHz
DSN 70m	0	+6 dB
DSN 34m	-6 dB	0
DSN Array	**13.9 dB**	**19.9 dB**

ADVANTAGES OF A LARGE ARRAY

- LARGE DECREASE IN COST PER DECIBEL OF LINK MARGIN
- SIMPLIFIED SPACECRAFT TELEMETRY HARDWARE
- FLEXIBLE SCHEDULING – SIMULTANEOUS TRACKING OF MULTIPLE SPACECRAFT OVER WIDE AREA OF SKY
- NEW SPACECRAFT NAVIGATION CAPABILITY: REAL TIME, HIGH PRECISION ANGULAR POSITION MEASUREMENTS – COMPLEMENTS RANGE DATA AND PROVIDES FULL 3-D SPACECRAFT POSITIONS WITHOUT NEED FOR MODELING
- HIGH RELIABILITY – GRACEFUL DEGRADATION OF ARRAY PERFORMANCE IF INDIVIDUAL ANTENNA ELEMENTS FAIL; MOVING MECHANICAL PARTS ARE SMALL & LIGHT WEIGHT; SIMPLIFIED OPERATIONS AND LOW-TECH MAINTENANCE
- ARRAY IS CONTINUOUSLY EXPANDABLE AND UPGRADABLE
- INCREASE SCIENTIFIC OUTPUT OF DATA-RATE-LIMITED MISSIONS: NGST, SPACE-BASED INTERFEROMETERS
- ENABLE NEW TYPES OF MISSION: RADIO OCCULTATION MEASUREMENTS WITH VERY DISTANT SPACECRAFT, DIRECT RECEPTION OF LANDER/ROVER/PENETRATOR SIGNALS ON EARTH, MULTI-SPACECRAFT VLBI ARRAYS, SPACECRAFT WITH NO ON-BOARD DATA STORAGE, DOWN-LINKS WITH BOTH HIGH DATA RATES AND HIGH DUTY CYCLE

Comparison of Array Requirements for Communication and Radio Astronomy

Parameter	Communication	Radio Astronomy
Frequency	8 and 32 GHz	.5 to 20 GHz
Array Configuration	Any but lower cost if closely packed	Sparse for better image sharpness
Element Size	Minimum cost probably in the 3.5 to 10 meter range	May be slightly larger because of more complex receivers
Data Processing	Digital beam forming of< 10 beams	Correlation processing of full image; > 10,000 beams
Bandwidth	<10 MHz	1000 MHz

Request for Information and Cost Estimates Sent to Antenna Manufacturers by JPL

Specifications - January 26, 2000

Microwave Antenna Array Element

General Description - A parabolic reflector including motorized angular position drives, feed support system, and foundations is required for use in a receive-only large array located in the southwestern U.S.

Primary Reflector Diameter - 5 meters. Focal length and subreflector system are unspecified at present.

Surface and Pointing Accuracy - Two options, for 8 GHz and 32 GHz operation, are being considered with the following accuracy requirements:

	Option A - 8 GHz	Option B - 32 GHz
Surface Accuracy	1.2mm = .046"	0.3mm = .012"
Pointing Accuracy	.05 Degrees	.012 Degrees

Surface accuracy is the rms deviation from a best fit paraboloid caused by gravitational, wind up to 15 mph, and temperature variation of -10 to 55C.

Pointing accuracy is the rms deviation of non-repeatable difference between commanded position and RF beam position caused by drive system error, wind up to 15 mph, and temperature variation of –10 to 55C. A computer-generated pointing correction table for each antenna is allowable.

Slew and Scan Rates – The drive system must be capable of slewing to any commanded position within 2 minutes of the applied command (180 degrees per minute in azimuth). Accurate pointing of the antenna must be maintained at speeds of up to 2.5 degrees per minute.

Pointing Position Range – The antenna drive system must allow pointing from 10 degrees above the horizon to 10 degrees past zenith in elevation and 360 degrees in azimuth.

Control Interface – Monitor and control interface of antenna position shall be through an optically-isolated serial interface.

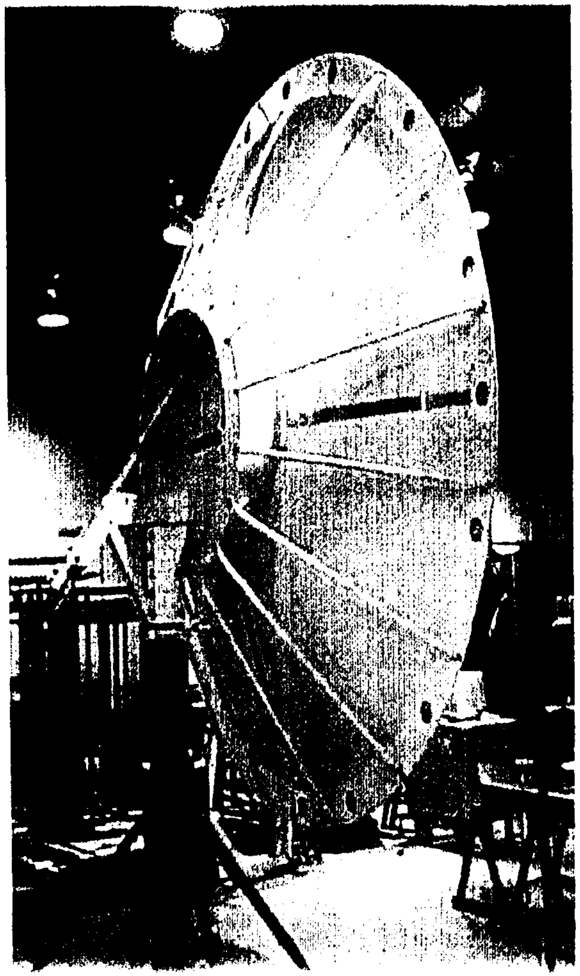
Receiver Mounting – The antenna shall include provision for mounting a 50 lb receiver feed and front-end assembly.

Wind Survival - The antenna drive system shall be capable of driving to stow position in a 40 mph wind and survive in stow position with 100 mph wind.

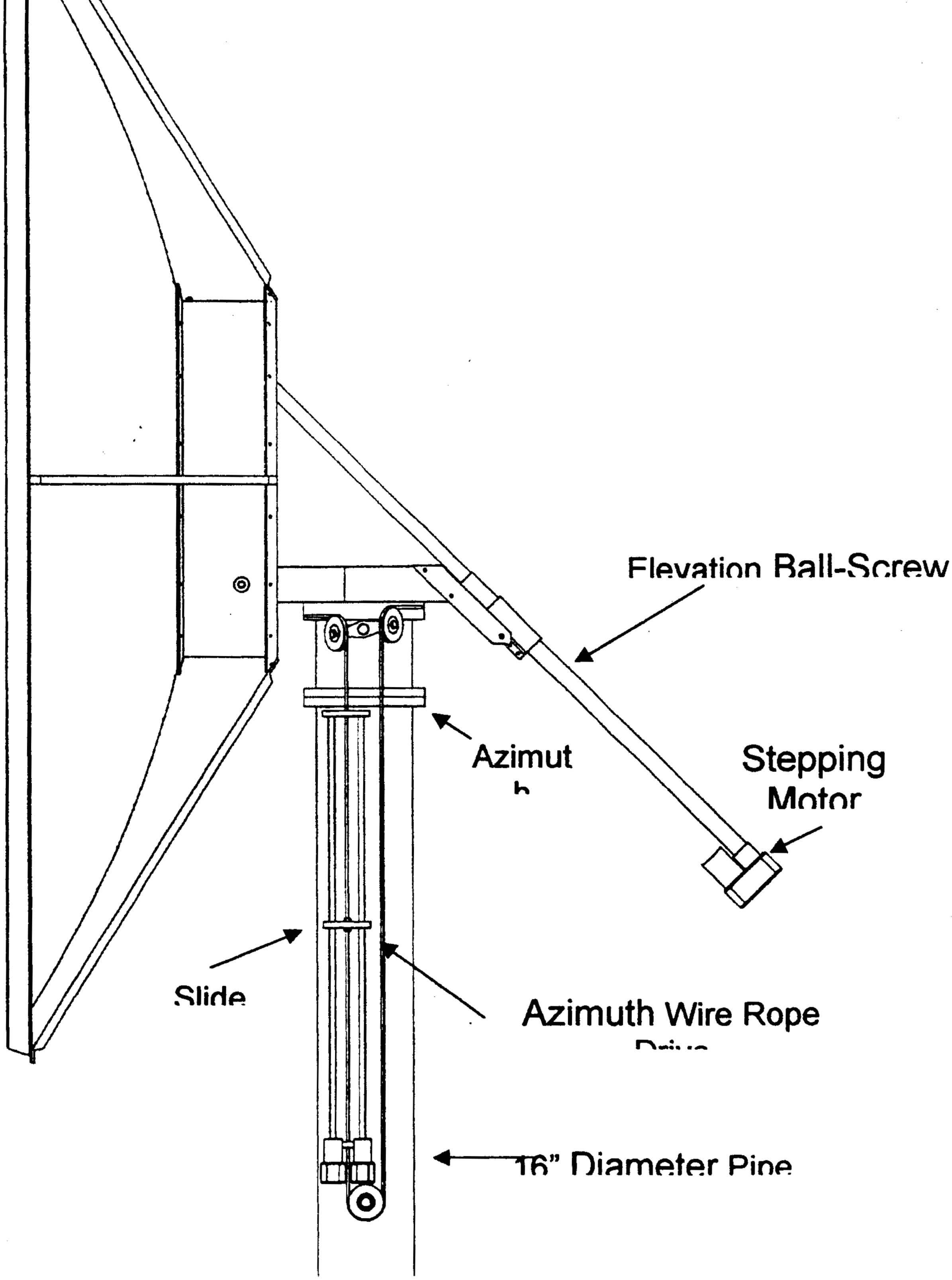
Andersen 4.2m Stamped Aluminum Antenna

- High accuracy surface formed by pressing aluminum sheet into precision steel die
- Low material cost and low fabrication labor hour requirement leads to low cost
- Prototype 4.2m has rms of .023" departure from design paraboloid
- Shell stucture has high rigidity supplemented by simple bolted rod and hat backup structure

Simple azimuth and elevation ball-screw drive mechanism is under development

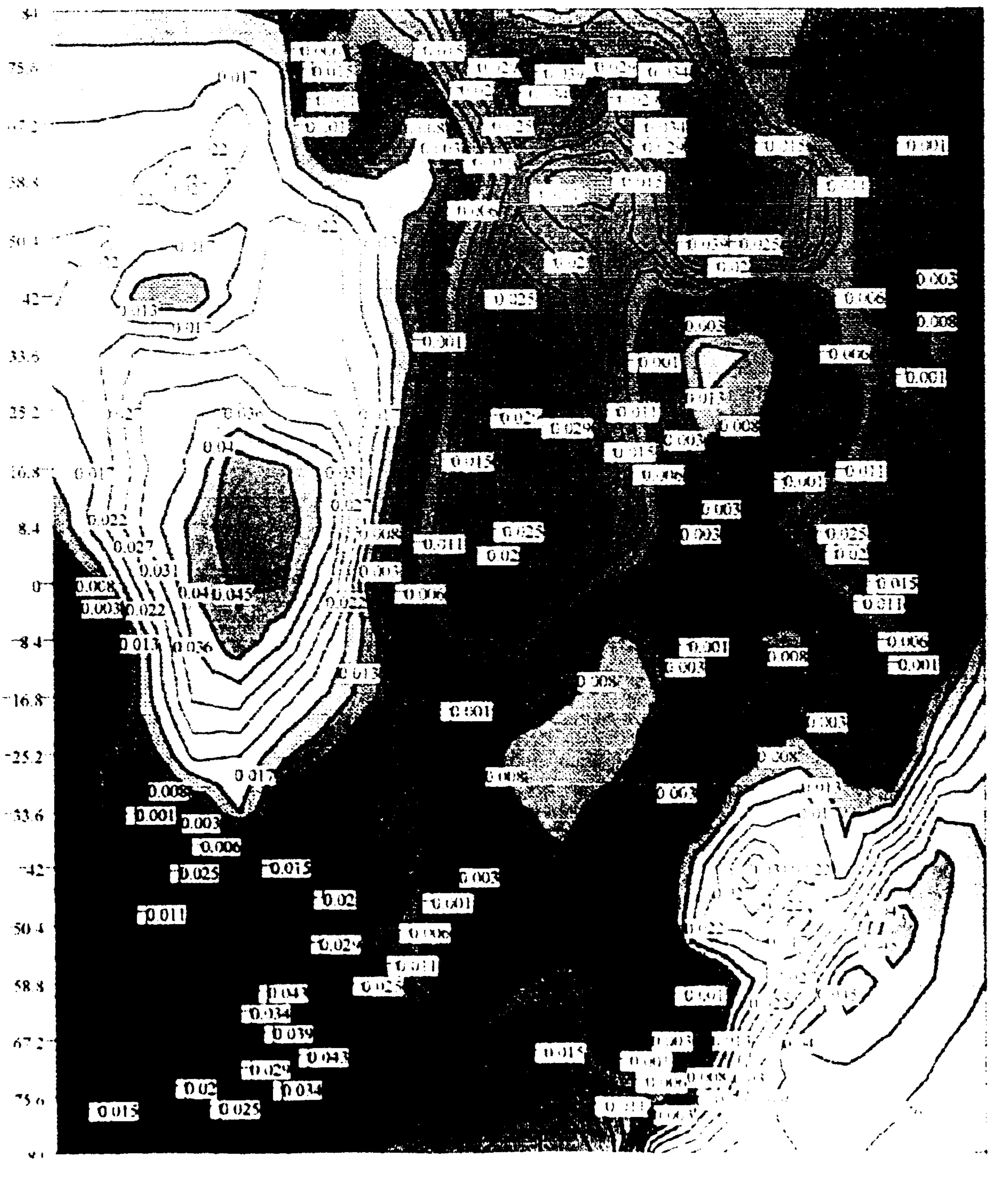


Andersen Azimuth and Elevation Drive Concept for 5m Antenna



Surface Error Contour Map
Andersen Prototype 4 2m Reflector, May, 2000
RMS= .023"=0.58mm /16 @ 32 GHz

Surf Cont Plot 4.2M True Focus Antenna (ASS14C), 03/29/00
Unptd., 1 PC. skin, Read on Mount Assm.. Focal Length: 63.54"



D = 169.44"
= 14.12'
= 4.30 m
F = 63.54"
F/D = 0.375

TRUE FOCUS Satellite Antennas

Price List - March 1998

Description		Mount	Quantity				Crate
Model	Size		1 - 3	4 - 10	11 - 50	50 +	Charge
O .75A	30" (.75M)	AZ-EL	$107	$101	$96	$92	
O .75P	30" (.75M)	PAN	$120	$113	$107	$103	
O .75U	30" (.75M)	UNIVERSAL	$170	$163	$156	$149	
O .9A	36" (.9M)	AZ-EL	$128	$123	$119	$113	
O .9P	36" (.9M)	PAN	$140	$130	$125	$120	
O .9U	36" (.9M)	UNIVERSAL	$193	$185	$178	$170	
O 1.0A	42" (1.0M)	AZ-EL	$150	$145	$140	$135	$10
O 1.0P	42" (1.0M)	PAN	$169	$162	$158	$150	$10
O 1.0U	42" (1.0M)	UNIVERSAL	$215	$207	$200	$192	$10
O 1.2A	48" (1.2M)	AZ-EL	$160	$155	$150	$147	$10
O 1.2P	48" (1.2M)	PAN	$182	$177	$170	$162	$10
O 1.2U	48" (1.2M)	UNIVERSAL	$225	$217	$210	$200	$10

Prices Above Include The Following:

1. TRUE FOCUS Hydroformed High Performance Antenna
2. Marched Optimized KU Band Single Polarity Feed Horn
3. Feed Support Boom With Fixed Feed, 360 Degree Polarity
4. Mount Config.: I.E. Pan, Ring, or AZ-EL
5. All Items Painted
6. Crated and or Boxed

Description		Quantity				Mounts					Crate
Model	Size	1 - 5	6 - 99	100 - 1000	1000 +	AZ-EL	Polar	Ring			Charge
O Series Offset Antennas											
O 1.8M	6' (1.8M)	$250	$233	$225	$215	$65					$90
O 2.4M	8' (2.4M)	$650	$600	$575	$530	$100					$135
P Series Prime Focus Antennas											
P 4	4' (1.2M)	$135	$125	$95	$85	$55	$70	$35			$30
P 4.5	4.5' (1.4M)	$140	$130	$100	$90	$55	$70	$35			$30
P 5	5' (1.5M)	$145	$135	$125	$120	$55	$70	$35			$30
P 6	6' (1.8M)	$190	$180	$175	$160	$55	$70	$40			$40
P 610	6'10"(2M)	$260	$240	$200	$190	$55	$70	$40			$100
P 8	8' (2.4M)	$280	$260	$225	$220	$80	$80				$110
P 8H	8' (2.4M)	$280	$260	$225	$220	$80	$80				$110
P 8C	8' (2.4M)	$395	$375	$350	$340	$90					$110

Description		Quantity				Mounts					Crate
Model	Size	1 - 5	6 - 25	25 - 100	100 +	AZ-EL	Polar	Stantion			Charge
4 P10	10' (3M)	$1,395	$1,375	$1,350	$1,300	$350	$400	$125			$175
4 P12.5	12.5' (3.8M)	$2,090	$1,925	$1,860	$1,800	$500	$550	$375			$275
4 P14	14' (4.2M)	$2,650	$2,510	$2,300	$2,250	$500	$550	$375			$300

1.8M Non-Penetrating Roof Mount	$275	Offset Single Pol C-Band Feed Kits	$85
2.4M Non-Penetrating Roof Mount	$375	Center Focus Single Pol C-Band Feed Kits	$85
Center Focus KU-Kit Single Polarity	$75	KU Digital / Analog LNB (.7)	$75
Offset KU-Kit Single Polarity	$20	25 Degree C-Band LNB	$75
		~~20 Degree C-Band Digital LNB~~	$150

All Orders Are F.O.B. Factory Idaho Falls, Idaho, USA

Antenna Element Cost Estimate for SKA

June 22, 2000

Find the Antenna Diameter, D, which minimizes the cost of an array with a specified total area

Antenna element cost, $A = C \bullet D^X$

Electronics cost per element = E

Then minimum total cost is for A/E = X/2 -1

X is in the range of 2.7 to 4

X=2.7 A/E = 2.86, X=3.5 A/E = 1.33, X=4.0 A/E = 1.0

Current Small Antenna Prices Including Mount

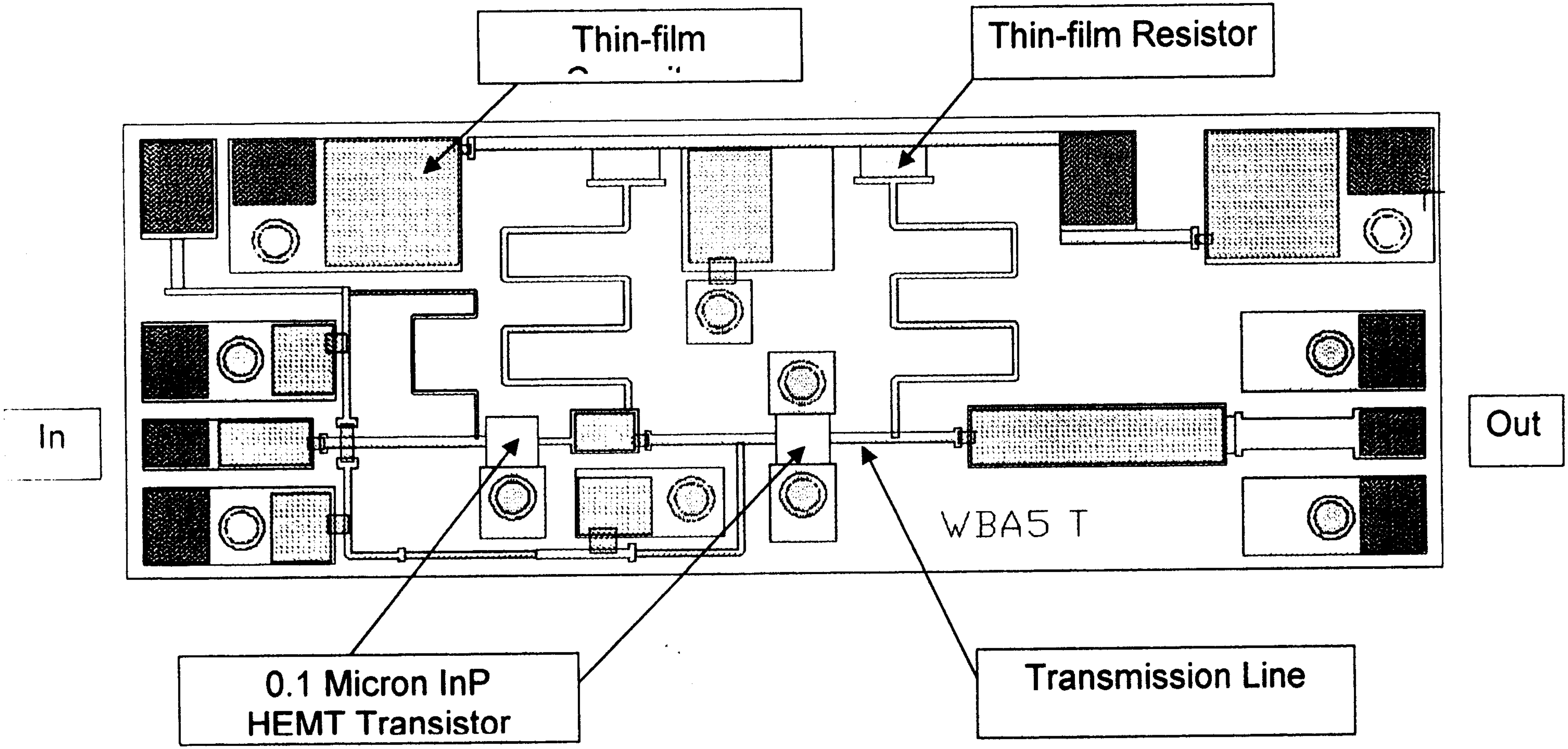
Skyvision 4.9 m - $4K, 7.3m - $16K, X=3.5
Orbitron 4.9 m -$2.5K (reflector only)
Andersen 4.2m – $3.4K (reflector only)
Andersen 5 m - $20K (Ka band with mount)
SETI 1HT 5 m - $15K?
Ref: www.skyvision.com, www.anderseninc.com

Array Antenna and Electronic Costs

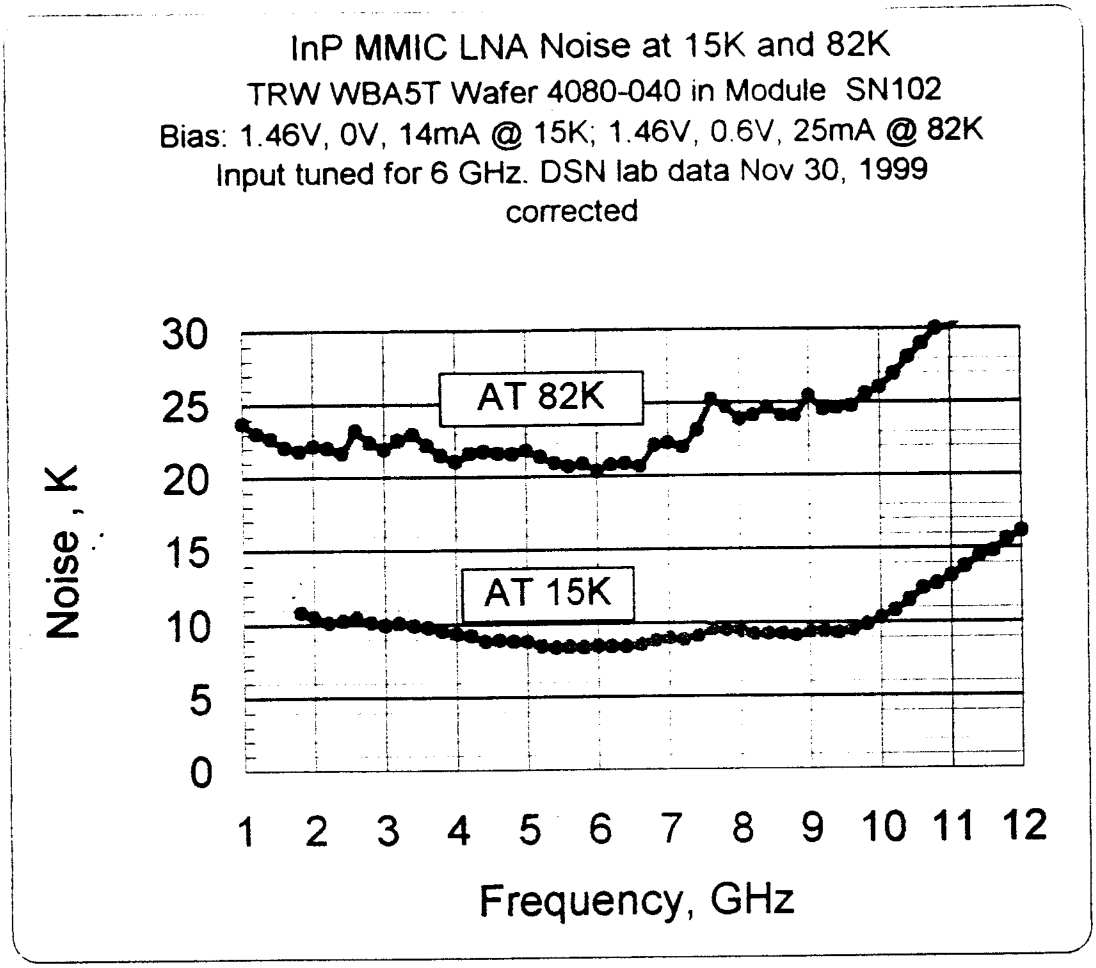
Equival. Antenna	N Elements	Antenna/ Electronic Costs	Total Cost
2 x 70 m	392 x 5m	$25K/$20K	$17.6 M
20 x 70m	3920 x 5m	$20K/$15K	$137M
SKA	10,000 x10m	$50K/$30K	$800 M

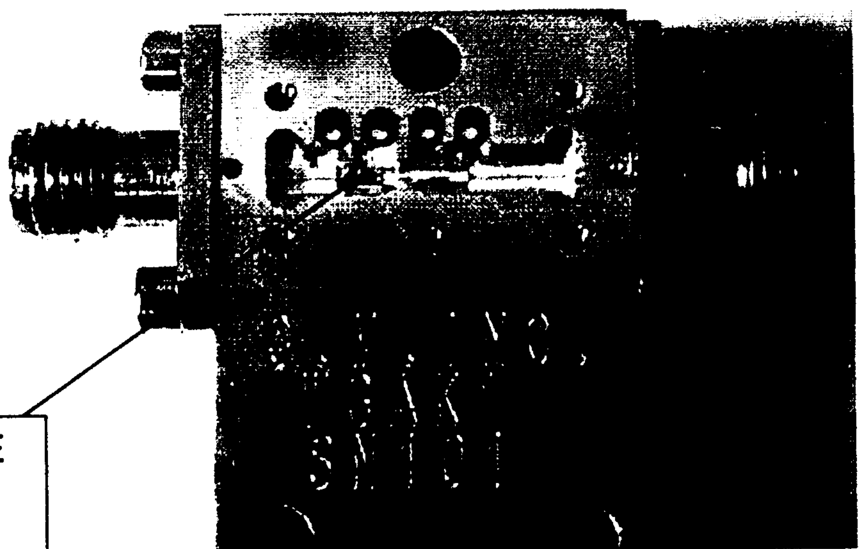
Monolithic Integrated Circuit Very Low Noise 0.5 to 11 GHz Amplifier

Chip Size – 2mm x 0.74mm x 0.1mm, Material – Indium Phosphide



Low-Cost, Wideband MMIC Cryogenic LNA





SINGLE
CHIP
LNA

DSN Array Technology Summary
March 5, 2000

Subsystem	Baseline Approach	Other Options
Array Configuration	Compact hexagonal grid within 5km area	Minimum redundancy array spread over wider area
Reflector antenna	5m solid surface shell	8m or 10m paneled surface
Feed system	8/32 GHz on-axis prime focus dual circular polarized	1-32 GHz off-axis Gregorian or prime-focus turret
Low noise receiver	MMIC InP HEMT LNA's @ 80K Tn = 15K at 8.0 – 8.8 GHz Tn = 30K at 31-33 GHz	Improved transistors for lower noise. Wider bandwidth for science applications
Cryogenics	Pulse tube refrigerator	Klemenko refrigerators or Nitrogen expansion system
Local Oscillator	Fiber coupled subharmonic; i.e. 2.0 – 2.2 GHz	Wider bandwidth system
Downconverter	Dual image-reject mixers into fiber-optical modulators	Bandpass filter image rejection
IF Transmission	Analog baseband in the 5-500 MHz range modulated on optical fiber.	A/D conversion at antenna and digital transmission on fiber.
Control and Monitor	Subcarriers on LO fiber	Standard protocols on separate fiber.
Beam Former	Digital time delay, phase adjustment, and summation with DSP chips	Cross-correlator for spectral and full image formation

Number of Digital Operations and Processing Cost

To form K beams from A antennas in bandwidth B with N frequency bands:

$$N_{OPS} = 3 \bullet K \bullet B\left(A + 2 \bullet LOG_2 N\right)$$

where N_{OPS} is the number of complex additions and multiplication's per second.

Processing Parameters for DSN Arrays with 76,000 m^2 Area

Case	5m Array, Com	5m Array, Imaging	Fixed Element Array
K, Beams	4	400	4
B, MHz	100	100	1
A, Antennas	4000	4000	335E6
N, Frequencies	1	1000	1
Nops, GFlops	4800	482, 400	4E6
Cost, 2000 (1)	$1.9M	$193M	$1.6B
Cost, 2005 (2)	$190K	$19.3M	$160M

(1) Year 2000 DSP cost, $400 per GFlop
(2) GFLop cost down 2 dB per year (Moore's Law)
(3) Fixed element array with hemisphere coverage

DSN/SKA Proposed Schedule

June 22, 2000

Milestones

Date	Action
Nov, 1999	JPL meeting; decision to write DSN proposal
Feb 28-29, 2000	Meeting of U.S. SKA Consortium at Arecibo
Mar 1, 2000	Industry replies to JPL request for cost estimates on 5m 8 and 32 GHz antennas
Apr 1, 2000	Five page development proposal to NASA
May 15, 2000	Decadal plan for astronomy to NSF and NASA
Aug 2000	Jodrell SKA Meeting
Jan 2001	JPL Start Design of 400 x 5m Array
Jan 2003	JPL Start Construction of 400 x 5m Array
Dec 2004	Completion of 400 x 5m Array
Jan 2006	Start 4000 x 5m Array for RA and DSN
Dec 2009	Complete 4000 x 5m Array
Jan 2010	Start SKA 10,000 x 10m Array
Dec 2014	Complete SKA